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EVALUATION OF EXPLOSAFE EXPLOSION SUPPRESSION SYSTEM FOR AIRCRAFT FUEL TANK PROTECTION

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A joint USAF/Canadian government development program conducted during the period July 1977 to July 1980, to evaluate the fuel tank ullage explosion suppression performance and to qualify the airborne military use of EXPLOSAFE® void filler material, is reported.

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SUMMARY

Fuel tank ullage explosion resulting from ignition of vapors by various means is a major cause of military aircraft loss in combat. Over the years, many concepts which seek to prevent or suppress such explosions have been explored. Nitrogen dilution, chemical quenching and polyurethane foam explosion suppression materials have emerged as the primary candidate systems.

This report presents the results of a four-year performance study and qualification test program conducted on Explosafe, one of the latest, most advanced explosion suppression material. This is an expanded metal mesh manufactured from thin aluminum foil. Coiled, or otherwise layered into a three dimensional structure of controlled density, it can be shaped to match the interior geometry of fuel tanks and installed through existing access areas.

The system has the passive, logistics-free advantages of the foam filler materials, yet, because of its metallic nature, it is free of limitations on operating temperature; is hydrolytically stable; and does not encourage electrostatic charge generation during fuel filling operations - the primary disadvantages of polyurethane foam materials.

A weight optimized configuration of thickness, expansion, web strand width and layering of the aluminum foil has been established at 2 lb/ft^3. The performance of this optimized arrangement has been proven satisfactory from the standpoints of ballistic impact, slosh, vibration, compaction, contamination, corrosion, static attenuation, fuel displacement, fuel retention, handling and installation. While installation and removal can present some difficulties, the system in its present form is equal or superior to tank filler materials previously used or contemplated for equivalent explosion protection, and is now ready for use in airborne applications.

Even though the dry weight of the material is somewhat greater than that of other explosion suppressant materials, its overall effect on aircraft range is comparable due to its lower fuel retention and displacement characteristics.

The Explosafe explosion suppression system has been developed by the Explosafe Division of Vulcan Industrial Packaging Limited (VIPL) of Canada, and is currently in use in a variety of surface vehicles. In view of the many proven advantages offered by the Explosafe system in reducing or eliminating fuel tank explosion hazards, it must be concluded that the system now merits serious consideration for application wherever such hazards exist.

Initial combustion tests on Explosafe conducted at Wright-Patterson Air Force Base, Aero Propulsion Laboratory were sufficiently promising to warrant a program of tests and demonstrations to study all factors relating to the use of Explosafe as a passive system for aircraft fuel tank protection. The program was conducted by the USAF and VIPL under a joint USAF-Canadian Government contract. The positive results obtained have justified the extensive effort involved in determining the practicality of the system for future airborne applications.

The test program was divided into two phases:

a) Phase I was conducted jointly by AFWAL and the US Army to characterize the explosion suppression performance of the system, with regard to its manufacturing variables, in "worst case" laboratory and full scale ballistic environments. This work is reported as Task I.

b) Phase II was conducted by the manufacturer of the material, sub-contracted by the Canadian Government. Their responsibilities were: to determine if the material would withstand operational and environmental conditions to which it would be subject in

airborne military service; to demonstrate that the material would not affect aircraft operation; to explore the feasibility of its installation; and to define the physical properties and operational penalties of the system. These various areas of study are reported in Tasks II through IV.

Task I

In Task I, the evaluation conducted by AFWAL studied the effects of material orientation, specific weight and specific surface area on performance using electrical discharge ignition of a "worst case" propane/air mixture. It was concluded that the material orientation was not significant and the optimum material was one having a specific weight of 2 lb/ft^3 manufactured from .002 inch foil. This material met the overpressure requirements of MIL-B-83054 B for types I, II and IV with a material maximum allowable void volume of 10%.

The US Army evaluated a narrower range of material variables by subjecting them to typical ballistic threats in tanks of varying sizes. The optimum selection was confirmed and demonstrated the ability to withstand threats up to 23 mm HEI-T with acceptable overpressures in typically voided configurations. The report describes further tests wherein an external wing tank equipped with the optimum material was exposed to the same threats and dramatically demonstrated the performance.

Task II

In Task II, the manufacturer defined the materials' properties and its effect on fuel systems. The relationships of material specific weight and specific surface area to foil expansion and thickness were established. The level of entrained solid contamination was measured under both laboratory and field conditions, successfully meeting the military requirement.

The penalties of fuel displacement and fuel retention were defined, again under both laboratory and field conditions. This data is

used to evaluate the system weight penalty and effect on usable fuel in a typical fuel tank. In a static system comparison with the latest type of polyurethane foam explosion suppression, the lighter weight of the latter is offset by the greater usable fuel of the Explosafe system. In a dynamic situation, further reduction in fuel retention with the polyurethane foam and the Explosafe material can be anticipated.

The material was found to have no effect on fuel system operation with regard to flow, flight inversion, and vent icing characteristics. The additional benefit of slosh suppression was evaluated, demonstrating reduction in dynamic wave forces by an order of magnitude. In a study of the electrostatic charging/discharging characteristics of a fuel system using the material, reduced charge generation (no spark discharges) and the potential of continuous, safe charge dissipation were noted.

Task III

In Task III, the material was subjected to typical operational stresses and environmental exposures which included static loading, dynamic slosh, dynamic slosh with vibration in both metal and bladder tanks, dynamic vibration alone, and exposure to fuels, additives, and typical corrosive fuel contaminants. In each field of study, the material itself proved to be acceptable with insignificant effects on tank structures, coatings and environments.

Task IV

Finally, in Task IV, the feasibility of installing the material in fuel tanks of increasing complexity culminating in the center wingbox tank of a Fairchild-Republic A-10 aircraft was studied. Access was limited to existing apertures and a maximum void limitation of 10% was defined. The installations in the more simple fuel tanks were easily accomplished and, while demanding much design consideration and a great number of individual sections, the wingbox installation also was successfully demonstrated.

The test program has yielded a wealth of information on this candidate's performance, properties, manufacturing techniques and design criteria. This information is the basis of a military specification presently being drafted.

Explosafe explosion suppression material meeting that specification and engineered to conform with the design criteria is qualified for consideration for use in military aircraft. Actual selection for use will be determined by specific advanced aircraft system survivability needs and assessment of specific advantages offered compared to other state-of-the-art protection measures.

SECTION I

INTRODUCTION

Background

The problem of fuel tank explosions has been with us since the invention of the internal-combustion engine. The hazard is amplified under the ballistic threat to aircraft in combat. In fact, the most vulnerable parts of an aircraft are the fuel tanks.

In the 1960's, a polyurethane foam capable of suppressing explosions was demonstrated by U.S. and British authorities. The passive nature of this type of system and its associated reduction in logistic problems, together with full time protection, made it a viable alternative to the existing fuel tank inerting schemes employed at that time. The USAF experience in South East Asia further exemplified the vulnerability of its aircraft in the fuel tank area. The tropical climate of South East Asia subjected the foam to extremes of temperature and humidity which revealed deficiencies. The foremost was a lack of hydrolytic stability (humidity resistance). Limited service life of 2 to 5 years was experienced with the foam, and as breakdown occurred, fuel systems became contaminated and fuel filters were clogged.

The Air Force realized these problems and in 1967 initiated a Technical Need (TN) for a high temperature explosion suppression material for aircraft fuel tanks and dry bay areas (Reference 1). In 1970 another TN was initiated to evaluate advanced flame arrestor technology for aircraft fuel tanks. In 1974 this TN was updated to include the Explosafe material (Reference 2).

The objectives of both these TNs were two-fold:

a) to provide alternate materials to the present polyester polyurethane foam for use in high performance aircraft where temperatures can exceed 200°F.

b) to provide improved materials in terms of humidity resistance for use in current systems where temperatures do not exceed 200°F.

Explosafe, a fuel tank explosion suppression system, has been under development for some 25 years. In its present form it is an expanded aluminum foil matrix that was conceived in the late 1960's. Being metallic the material is able to withstand the high temperature environments and the aluminum alloy selected can tolerate high humidity. It therefore satisfies the TN expressed by the USAF.

The Explosafe material is manufactured by slitting, then expanding a thin aluminum alloy foil. The resulting material is then coiled or fan-folded into a 3-dimensional batt. In the first operation, a rotary gang-slitter is used to impart an offset series of interrupted slits to a 14 inch wide web of material. The width of each inter-connected strand, typically .055 inch wide, is determined by the thickness of the slitting knife employed. The second operation is a transition of the web from the slit to the expanded state. This is performed by advancing the slit web, held by its edge, continuously over a pair of divergent triangular arms. As the foil strands are separated, they form the sides of a series of irregular hexagons, as illustrated in Figure 1, and they also twist out of the plane of the web. This strand incline gives the web an increased effective thickness.

To prevent nesting of the inclined strands, adjacent layers of the material are inverted as shown in Figure 2, resulting in an edge to edge lay-up. The density of the material is thus controlled and settling or shifting eliminated. Opposed in this way, two webs can then be coiled into cylindrical batts. The preferred method of fanfolding however is shown in Figure 3. The web, creased perpendicular to its direction of travel, is allowed to fold along these regularly placed indentations. Using a single web the resultant layers contain strands twisted in the required

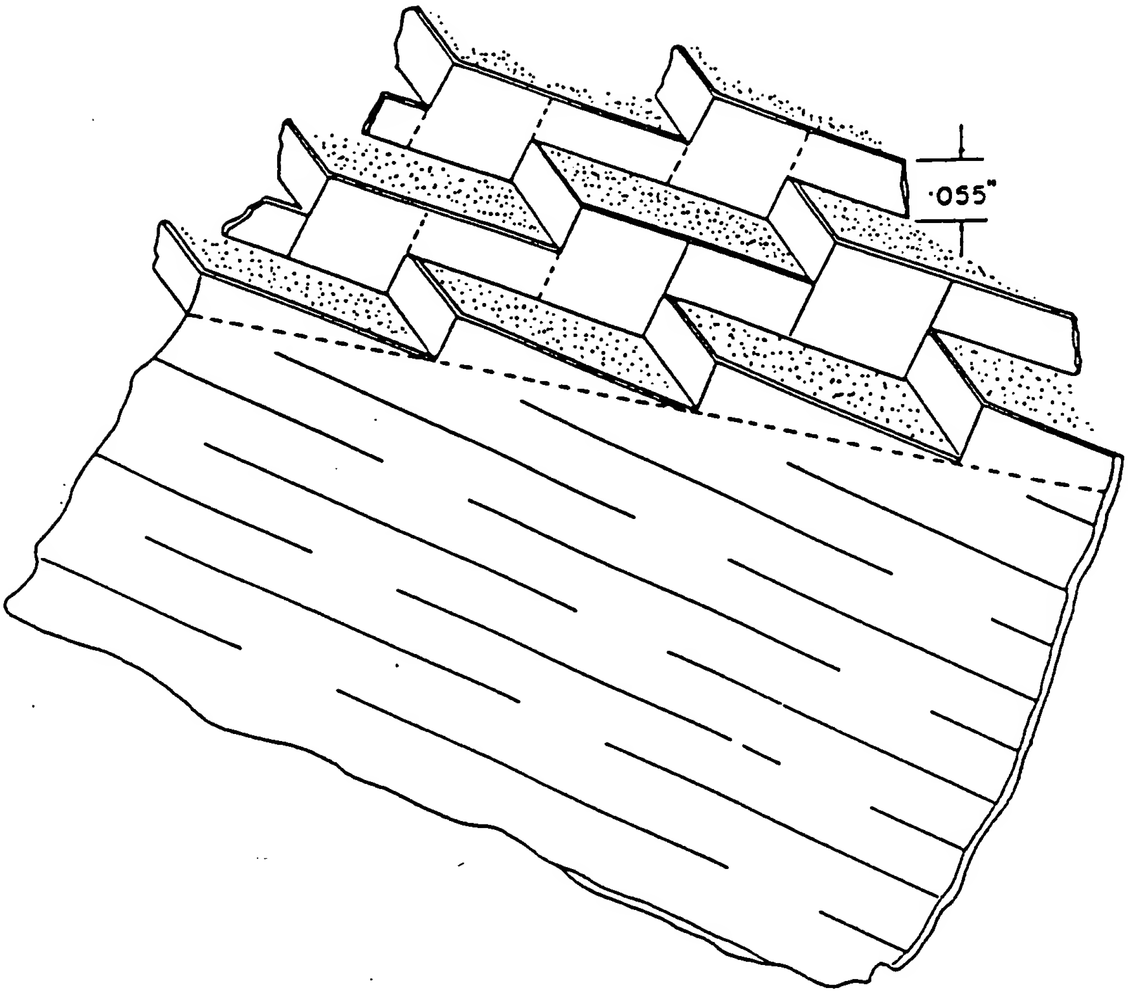

Figure 1. Transition from Slit to Expanded Foil

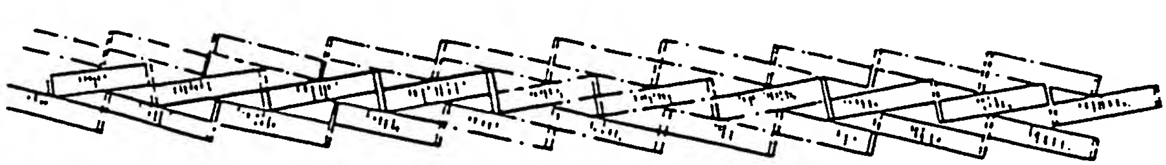

Figure 2. Layer Spacing in Opposed-Strand Layup

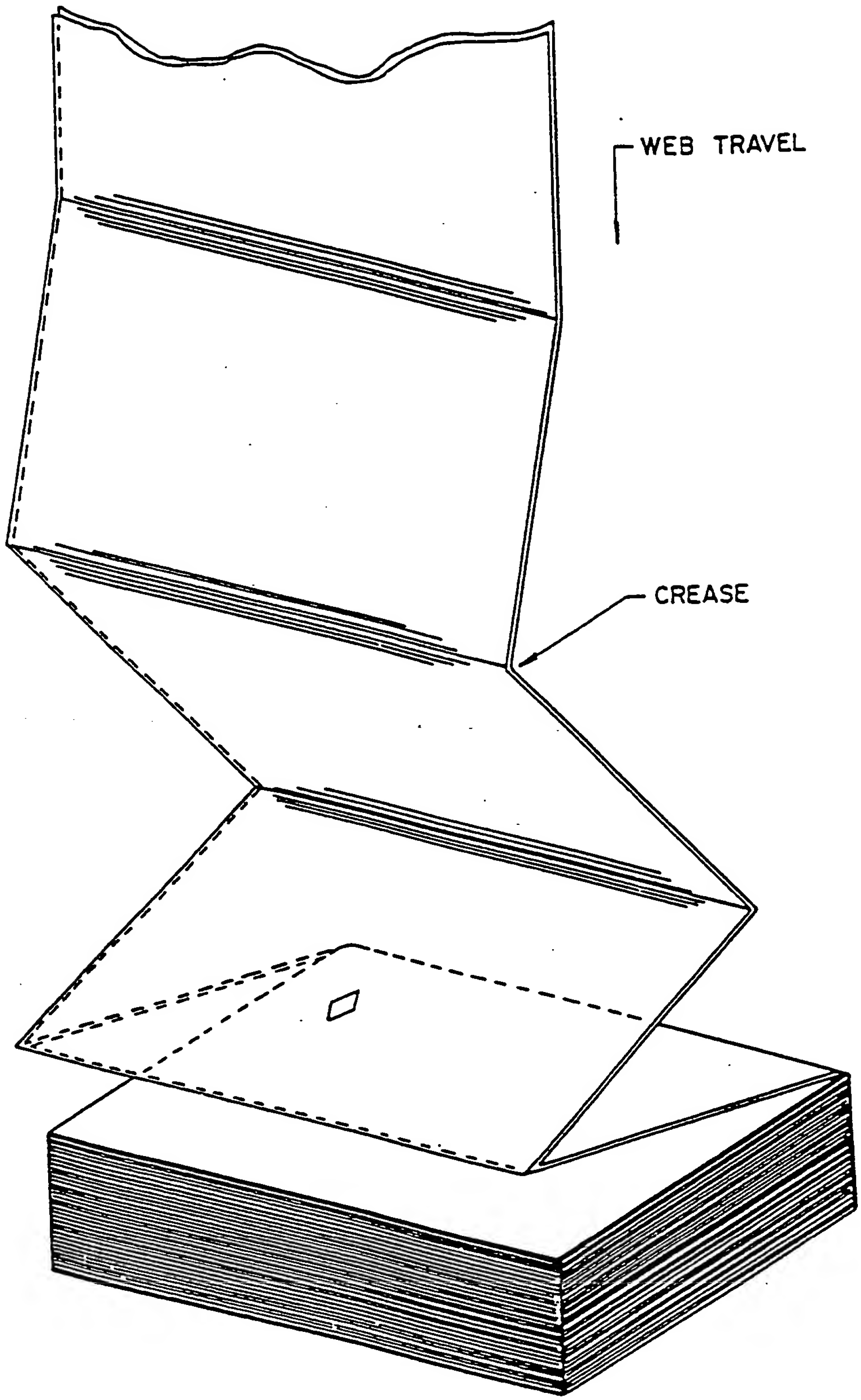

Figure 3. Fanfolding Expanded Foil into Rectangular Batt

opposite directions. The use of two opposed webs doubles the output of the fanfolder while maintaining the reversed layup.

The Explosafe Division of Vulcan Industrial Packaging Limited, (VIPL) is the developer of this technology. A Canadian Company, VIPL is involved in the world-wide marketing of the material.

Scope

The Explosafe system was introduced to the Air Force as a possible candidate in the search for an improved method of explosion suppression. Tests conducted by AFWAL/POSH and ASD/ENFEF during the third quarter of 1975 verified its ability to suppress explosions. In fact, the explosion suppression performance on this initial screening was equal to the large pore polyurethane foams. This performance, together with the advantages of being metallic, justified a research and development program to assess and qualify the material for use in aircraft fuel tanks. This was initiated in the form of a joint Canadian Government/USAF program to evaluate Explosafe. The contractor on this program was the Canadian Commercial Corp. who, in turn, sub-contracted Vulcan Industrial Packaging Limited, Explosafe Division, to carry out the contractor portion of the program.

The technical requirements of the program were divided between the contractor, who became responsible for the qualification testing, and the USAF/US Army who jointly assumed responsibility for the explosion suppression performance evaluation.

Objectives

The program was divided into four tasks:

Task I - Performance Testing

Phase I

Parallel series of tests were to be performed by VIPL and AFWAL to assess the effects of material orientation on suppression performance. On completion of this program, a trade off study

was to be conducted to evaluate, under laboratory conditions, optimum material configurations.

Phase II

Tests were to be conducted to assess the ballistic response of the material in its optimum configurations. This would be conducted jointly by the USAF and the US Army, and include API and HEI-T impacts. Blast attenuation and explosion suppression were to be investigated in a full scale simulator.

Task II - Material Properties and Effects on Fuel Systems

Tests were to be conducted on production explosion suppression material to establish significant physical properties and characteristics. Although emphasis was placed on the products' specific weight and its fuel displacement and fluid retention characteristics, tests were also to be performed to assess the operational characteristics of slosh suppression and electrostatic charge dissipation. Resistance imposed on fuel flow, susceptibility to vent icing under worst case airflow conditions and foil-entrained solid contamination were also to be examined.

Task III - Operational and Environmental Effects on Materials

Operational

Static tests were necessary to determine the ability of the material to withstand steady loads imposed either by storage or 'g' forces in operation. The effects of operational vibration were to be determined by cycling the material through typical frequencies and amplitudes while fuel was flowing. The continuous flow would allow continual monitoring of contaminants being generated by the vibration by intermittent filter sampling.

A simultaneous slosh and vibration test was to be conducted on a rubber bladder tank fully packed with the material to evaluate the interaction of the material with the soft, inner wall surface of the tank, and to assess the reaction of the foil to intense operating conditions. Here, disintegration, settling and compacting of the foil would be pertinent points of assessment.

In addition, two dynamic slosh tests were to be performed on a specially prepared 200 gallon external pylon tank packed with the material. Under investigation would be the influence of the material on typical sealant and corrosion preventive fuel tank coatings. Again, friability of the foil, and measurable settling or shrinkage of the material were factors to be appraised, together with shifts in orientation of the material. The slosh attenuating characteristic of the foil was to be photographically documented.

Both types of tests represent life-time fuel tank operating conditions.

Environmental

The chemical compatibility of the material with fuels, additives, tank construction/fuel system components materials, and fuel contaminants such as water were of primary concern to the evaluation. Tests and literature surveys were to be conducted in each of these areas to ascertain the durability and inert properties of the material in simulated or comparable environments and to determine its limitations, if any.

Task IV - Installation Studies

Installation studies were to be conducted on a range of aircraft fuel tanks to determine the feasibility of designing the material for installation into tanks of various complexity, and to evaluate techniques associated with shaping and bundling the material to accomplish these installations. The study was to be performed in three phases. Successive phases would deal with techniques required to design, fabricate and install the material into tanks of increasing complexity, culminating in installation for a fighter type wing tank complete with all associated integral plumbing.

SECTION II

TASK I - PERFORMANCE TESTING

1.0 COMBUSTION

1.1 Procedure

The procedure for comparatively evaluating explosion suppression performance has been established by MIL-B-83054B and is extensively described in Reference 3. Summarizing, the procedure consists of inserting the specimen system in a pressure resistant test chamber, known as a flame tube, having a minimum total volume of 5.0 cubic feet and a 100 square inch cross-sectional area. The flame tube used by the AFWAL is 7.5 cubic feet with a cross-section of 144 square inches. A propane/air mixture of the ratio which previously has been found to result in the highest combustion overpressure is created within the chamber, verified by bomb sampling, and ignited with a high energy spark source having a minimum 0.25 millijoules energy. Evaluation of the performance is based on the recorded overpressure vs time curve, with particular reference to peak overpressure and pressure rise time, with respect to the initial conditions. Visual observations of the reaction within the chamber and the condition of the specimens after test are also considered.

The testing conducted by AFWAL is fully reported in Reference 3, and it is on the results recorded therein that the Explosafe explosion suppression system is to be evaluated. VIPL conducted a parallel test program to confirm and augment the AFWAL effort. Small deviations in the test apparatus and procedure exist but the VIPL test contributed to the analysis of the AFWAL results. The VIPL apparatus and proceduresare described in Appendix A.

1.2 Results

The AFWAL test results are summarized here.

1.2.1 Orientation Study

The program studied the effects of the material orientation within the test chamber relative to the direction of flame propagation. The material, being a layered, asymmetric cell structure, might be expected to affect the flame propagation by virtue of the different surface area and cell geometry presented to an oncoming flame front in the three mutually perpendicular planes as illustrated in Figure 4.

The tests were conducted with the 3 mil material at an expansion of 38 inches yielding a specific weight of 2.75 lb/ft^3 and a specific surface area of 130.6 ft^2/ft^3. Initial pressures of 14.7 psia and 17.7 psia were tested. Some of the material submitted for these tests was oversized and, in modifying, was subject to damage and undersizing. Also, other material had shrunk during transportation and was therefore undersized. The resultant gaps between material and flame tube walls may have resulted in scatter and inconsistencies in the test data. It was decided to repeat the tests. However, the remainder of the program had to be started and with the intent of selecting the 'worst case' orientation for all subsequent testing, the data was reviewed. Despite the inconsistencies and scatter, it was possible to conclude that the orientation did not affect the suppression performance. The S33 orientation, as illustrated in Figure 4, was then selected for the subsequent testing because of its ease of handling and installation.

The repeat testing was conducted at the end of the program and Figure 5 illustrates the data. It is evident that the data scatter is greater than the inconsistent difference between each orientation, confirming the conclusion made from the first set of results.

1.2.2 Optimization Study

The second part of the combustion test program explored the effects of material specific weight and specific surface area on suppression performance. The intent was to define, if

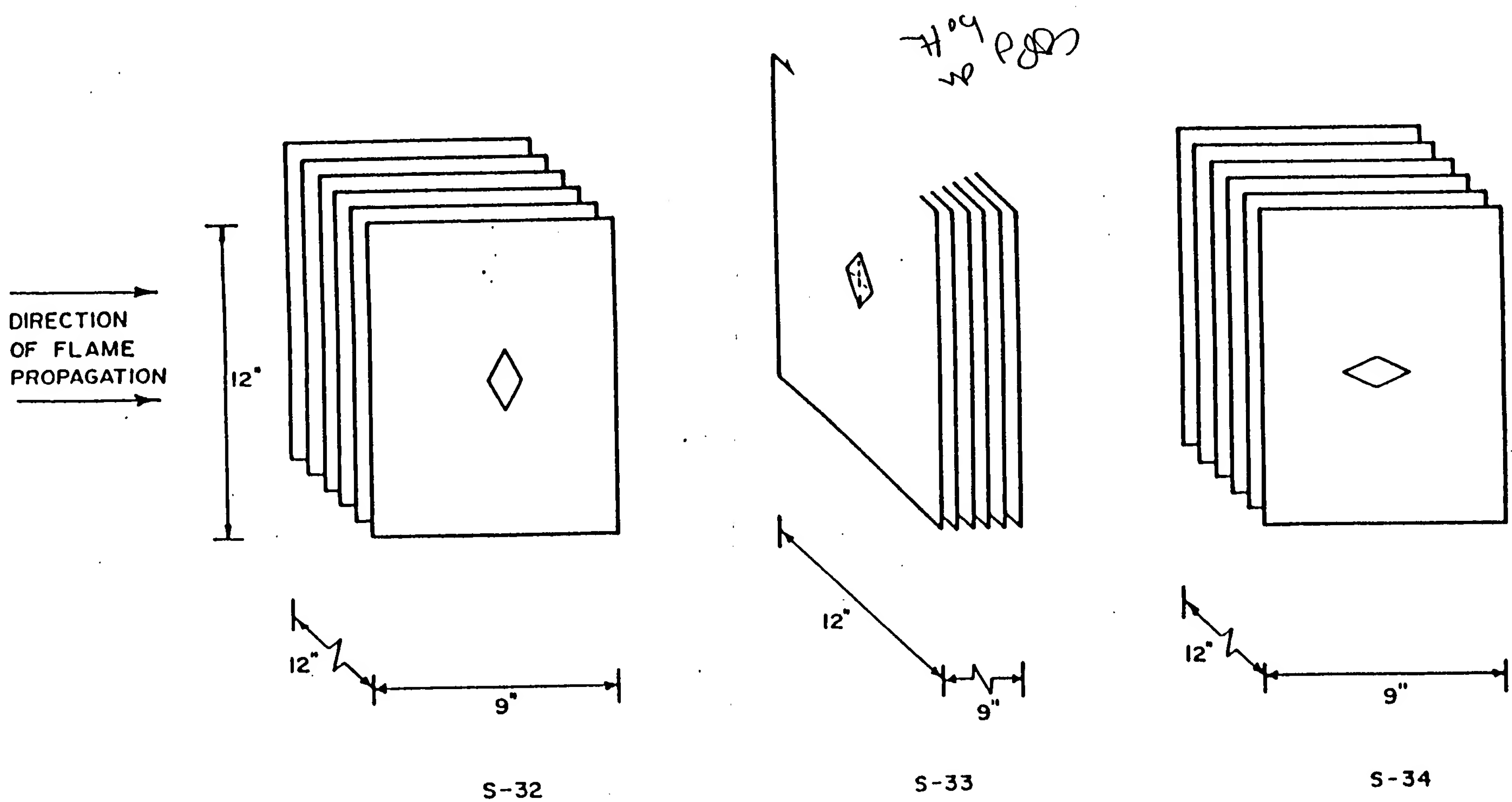

Figure 4. Foil Orientations

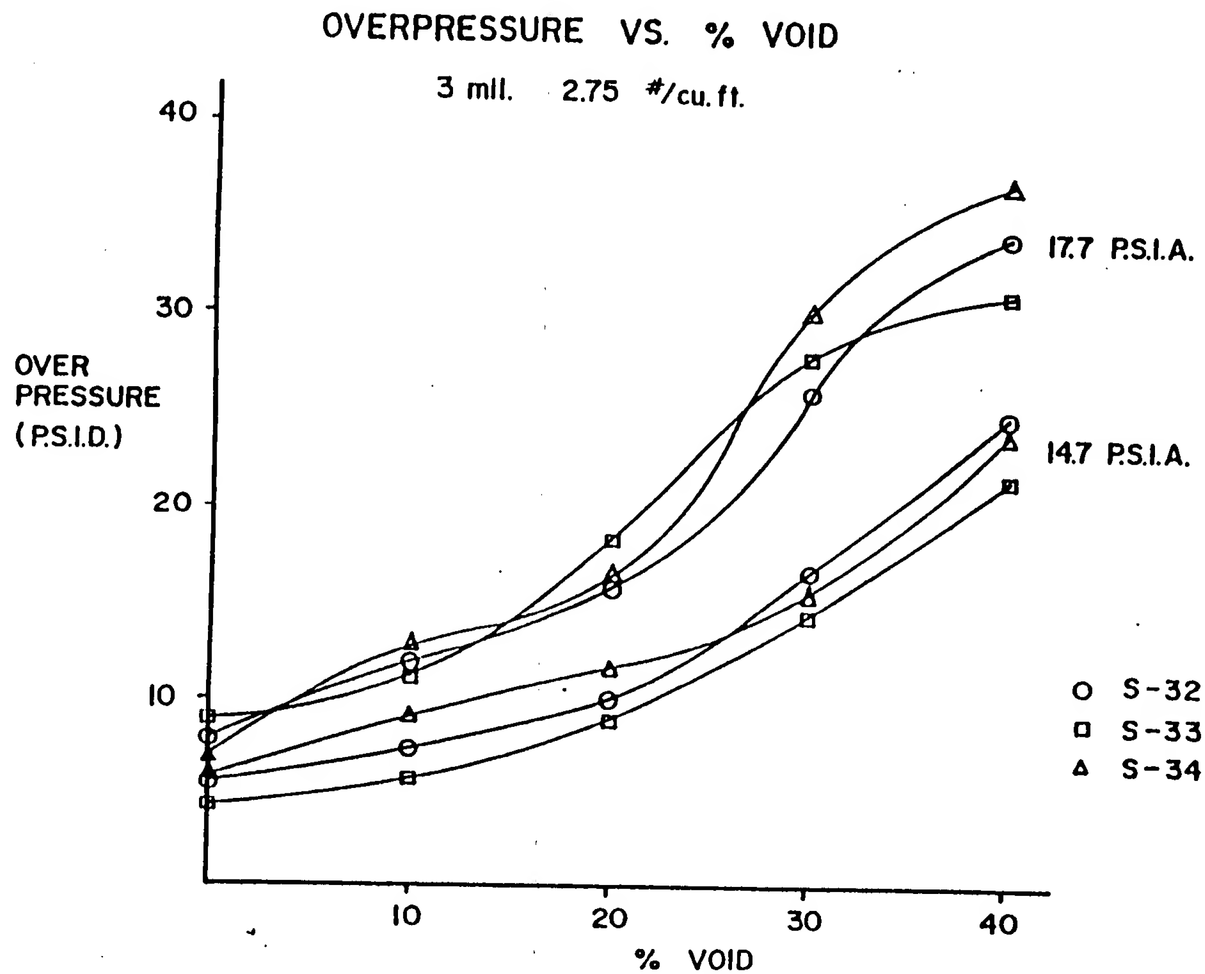

Figure 5. Orientation Study Results - Set 2

possible, an optimum material with regard to weight and performance, and involved testing with a range of material thicknesses, several expansion widths and combustion void levels (Vc). A summary of the results is presented in Table 1.

Figures 6 and 7 depict all the results plotted as combustion overpressure versus specific weight at initial pressures of 14.7 psia and 17.7 psia respectively. It is immediately apparent that there is a general trend of reducing overpressure as specific weight increases.

However, the individual sets of data for each foil thickness show a secondary effect which conflicts with the general trend; e.g. in Figure 7, the 2 mil foil at a specific weight of 2.17 lb/ft^3 consistently outperforms the 2 mil foil at the higher 2.33 lb/ft^3 and both of these outperform the 3 mil foil up to a specific weight of 2.75 lb/ft^3. The graphs suggest that for each thickness of material there is an optimum density.

The surface area of the Explosafe material is a function of the expansion and is sensibly independent of material thickness (strand edge area is ignored). Table 2 records this information as well as other properties of the samples under test. Figure 8 depicts some of the typical results obtained at an initial pressure of 17.7 psia plotting combustion overpressure versus material expansion (and hence surface area) for the 2 mil and 3 mil materials at various void levels. The overpressure with the 3 mil material is always lower than that with the 2 mil, confirming the general trend of reducing overpressure as specific weight is increased. The curves again show the secondary effect noted above which produces an optimum for each foil thickness.

To explain this behavior we will consider the properties of the material which influence the suppression performance, and examine the work conducted by VIPL to augment the AFWAL testing.

TABLE 1. COMBUSTION OVERPRESSURE TEST RESULTS

Combustion Void V_c (%)	Expansion (Inches)	ΔP_1 (psid) - Left Transducer					
		P_I, Initial Pressure (psia)					
		14.7			17.7		
		Thickness (mil)					
		1.5	2.0	3.0	1.5	2.0	3.0
0	32	6.4	5.0	3.5	12.5	7.5	6.5
	35		8.0			8.2	
	38	8.8		6.0	16.1		9.1
	Max. 44			9.4		13.3	11.6
10	32	7.6		5.5	18.5	13.0	8.5
	35		8.0			12.8	
	38	12.5		9.0	21.5		13.0
	44			12.8		19.8	18.2
20	32	20.5		8.8	23.0	20.6	14.5
	35		11.2			19.3	
	38	16.8		11.5	25.0		13.2
	44			13.4		25.3	26.8
30	32	29.0		12.5	37.0	31.0	25.0
	35		25.5			29.3	
	38	24.8		15.3	38.0		30.0
	44			16.6		34.0	33.0
40	32	37.5		26.5	45.0		43.0
	35					37.0	
	38			23.6			35.5
	44			24.0		51.0	41.8

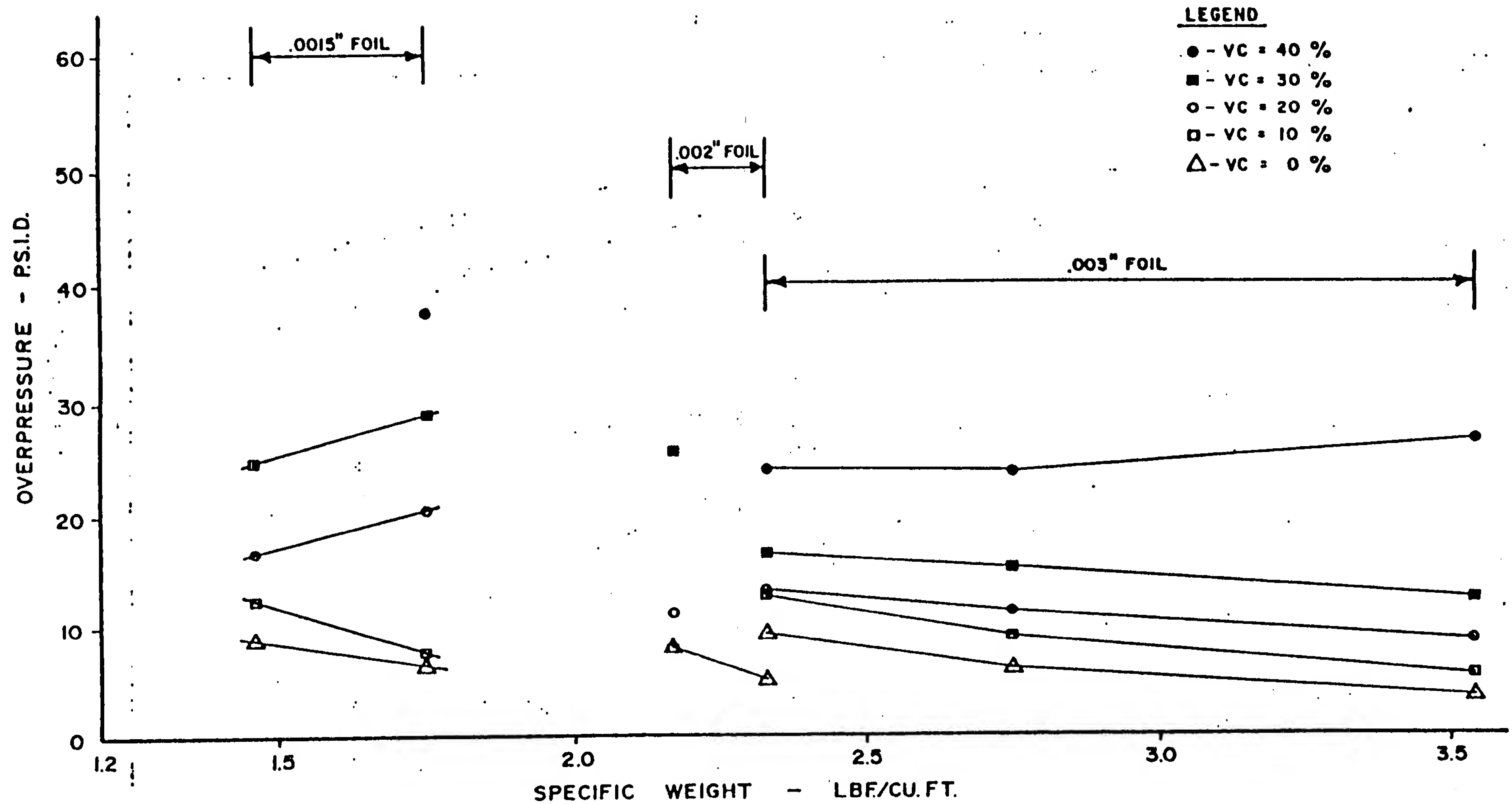

Figure 6. Optimization Study Results - Atmospheric Pressure

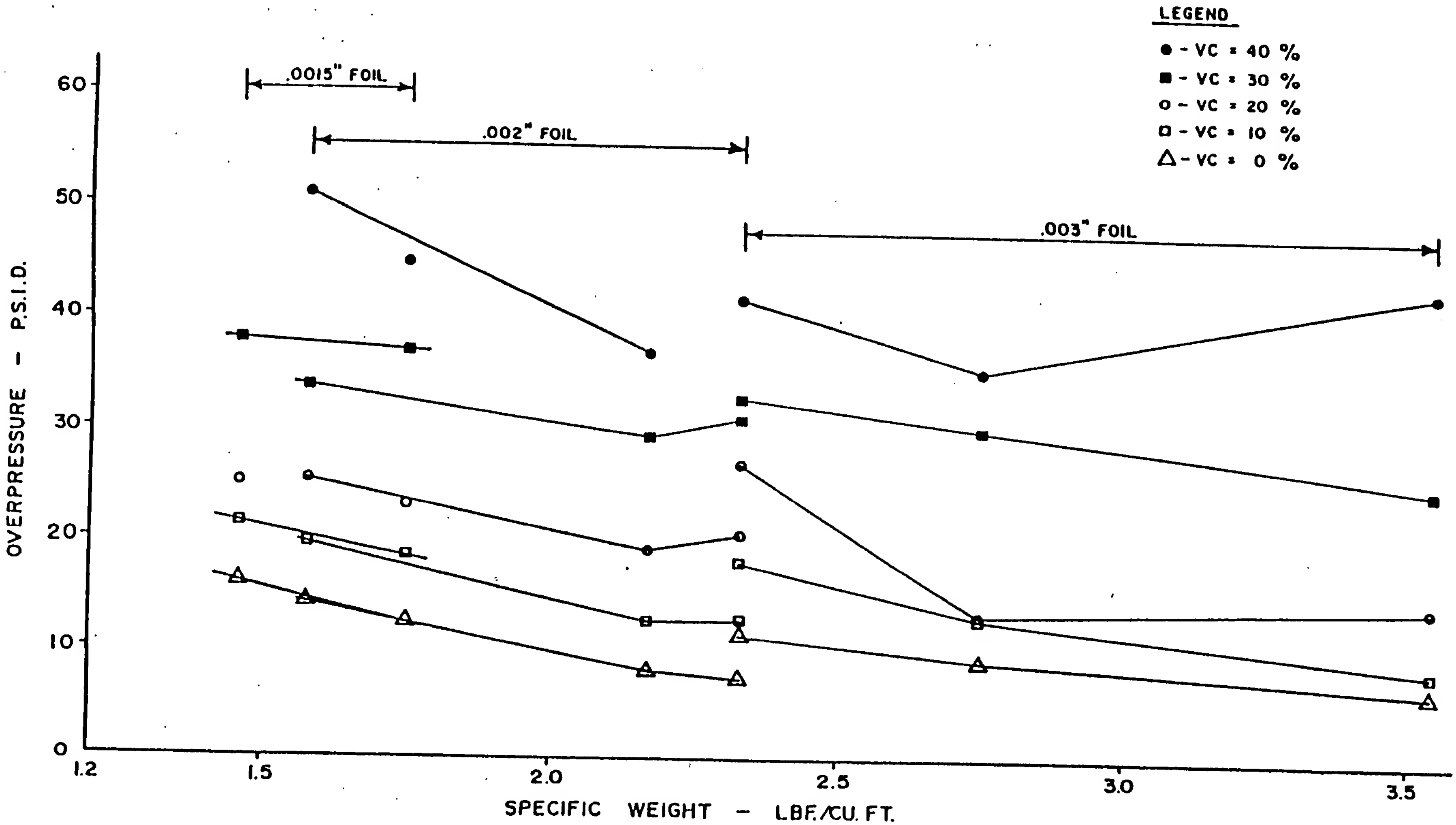

Figure 7. Optimization Study Results - 3 psig

TABLE 2. SPECIFIC WEIGHT AND SURFACE AREA VERSUS EXPANSION AND THICKNESS

Expansion (in)	Specific Weight (lbs/ft^3)			Surface Area (ft^2/ft^3)		
	Thickness (mil)			Thickness (mil)		
	1.5	2.0	3.0	1.5	2.0	3.0
32	1.75	2.33	3.54	166.3	166.0	168.2
35	(1.55)	2.17	(3.23)	(151.5)	154.6	(151.5)
38	1.46	(2.03)	2.75	138.6	(136.2)	130.6
44	(~1.20)	1.58	2.33	(113.5)	112.6	110.5

NOTE: Values in () are theoretical values

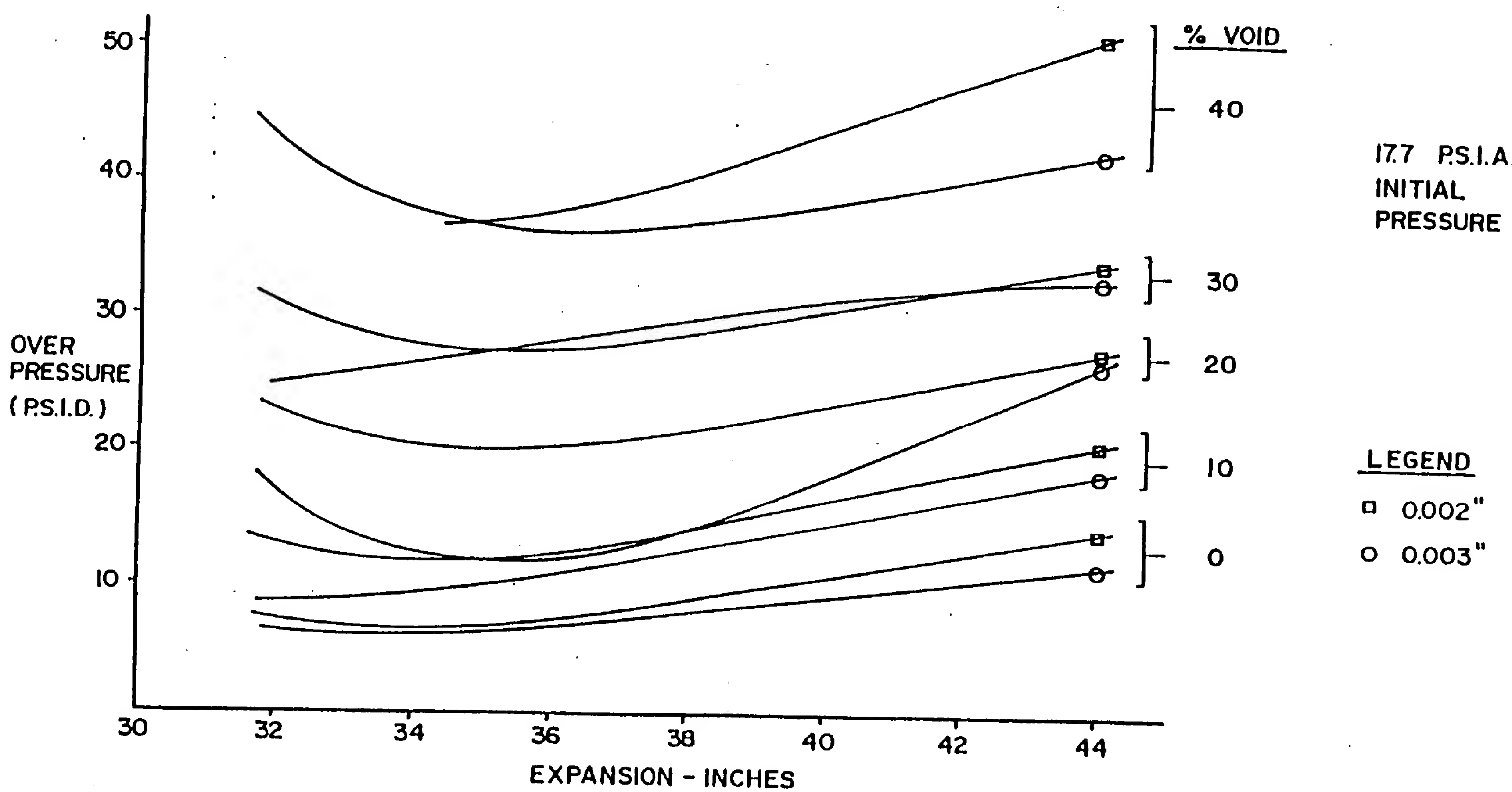

Figure 8. Effect of Foil Thickness on Combustion Overpressure

The Explosafe material is not a flame arrestor and the basic reason for its ability to suppress combustion overpressure is the rapid absorption of heat as the reaction proceeds. That ability is influenced by the mass of the material and by its surface area - these parameters were expected to control the heat capacity of the system and the heat transfer rate that could be achieved respectively. Figures 6 and 7 have shown this to be generally true with respect to the mass, but Figure 8 clearly demonstrates that there is a point beyond which increasing the surface area (reducing expansion) has a negative return and suppression performance deteriorates. This would defy the laws of thermodynamics, therefore, there has to be some secondary mechanism by which changing the expansion of the foil affects the heat absorption.

The only other characteristic of the material affected by expansion is the geometry of the cells. While, as noted earlier, the material is not a flame arrestor, it could locally quench a combustion reaction, particularly at the strand bond regions and interlayer contact points. The expansion controls the geometry and number of these areas and therefore, would influence the degree of quenching. By so doing, a secondary mechanism of suppression would be obtained; that of influencing the amount of heat released by the reaction.

To explore these theories, VIPL produced material with smaller cells for any given expansion by using a reduced strand width (.040 vs .055 inch). The properties of the two materials are identical with respect to specific weight and surface area. A full series of tests was conducted on the .040 inch strand width, 3 mil thick material with several expansions at various void levels and the two initial pressures. The test data is recorded in Table A-1 of Appendix A and is summarized in Table 3. The overpressures with the two cell geometries are illustrated in Figures 9 and 10.

TABLE 3. COMBUSTION OVERPRESSURE TEST RESULTS
.003 inch Material x .040 inch Strandwidth

Expansion (in)	Specific Weight (lb/ft^3)	Void (%)	0 psig Initial Pressure Overpressure (psid)	0 psig Initial Pressure Flamespeed (ft/sec)	3 psig Initial Pressure Overpressure (psid)	3 psig Initial Pressure Flamespeed (ft/sec)
33.5	3.49	0	2.2	29	4.6	37
33.5	3.49	20	5.7		9.3	
33.5	3.49	40	11.7		23.3	
35.0	3.26	0	2.1	18	3.7	29
35.0	3.26	20	5.8		7.5	
35.0	3.26	40	10.5		20.5	
38.0	3.00	0	3.8	21	5.0	33
38.0	3.00	20	7.1		14.5	
38.0	3.00	40	12.0		22.2	
42.0	2.78	0	2.5	22	4.8	39
42.0	2.78	20	6.0		12.8	
42.0	2.78	40	15.5		16.8	

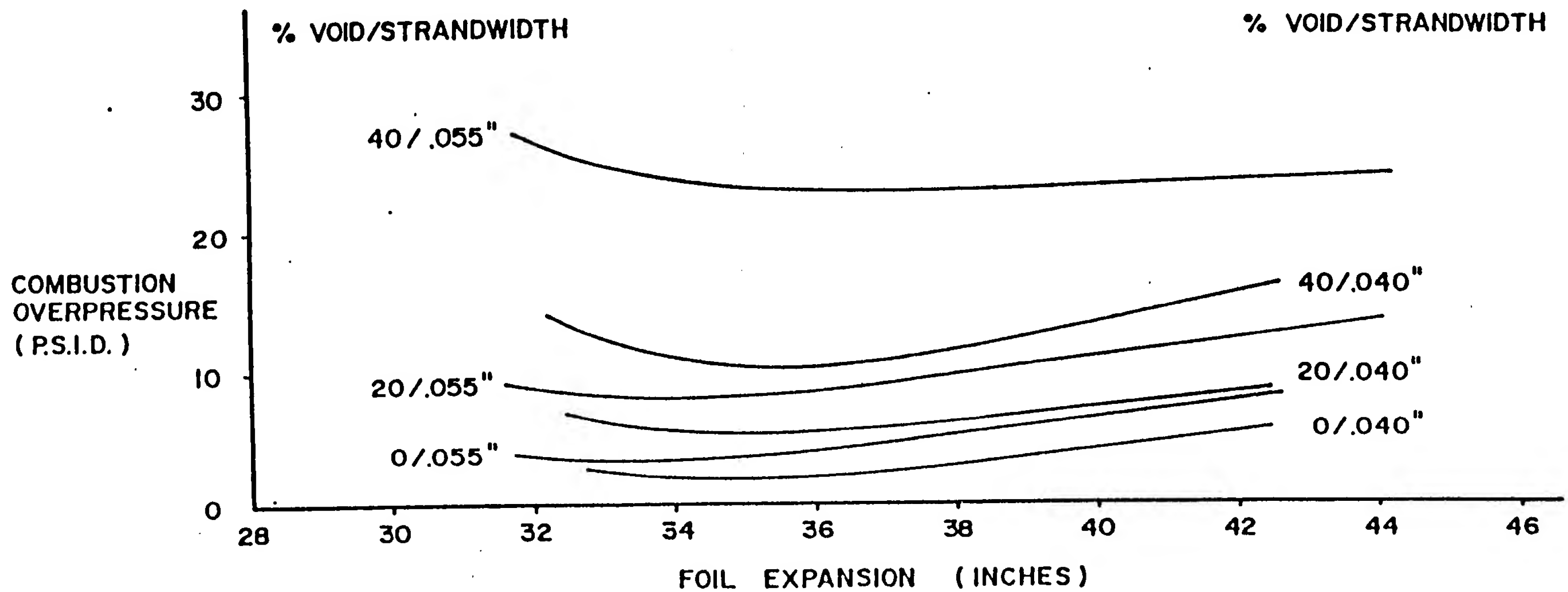

Figure 9. Effect of Strand Width on Combustion Overpressure - 0 psig

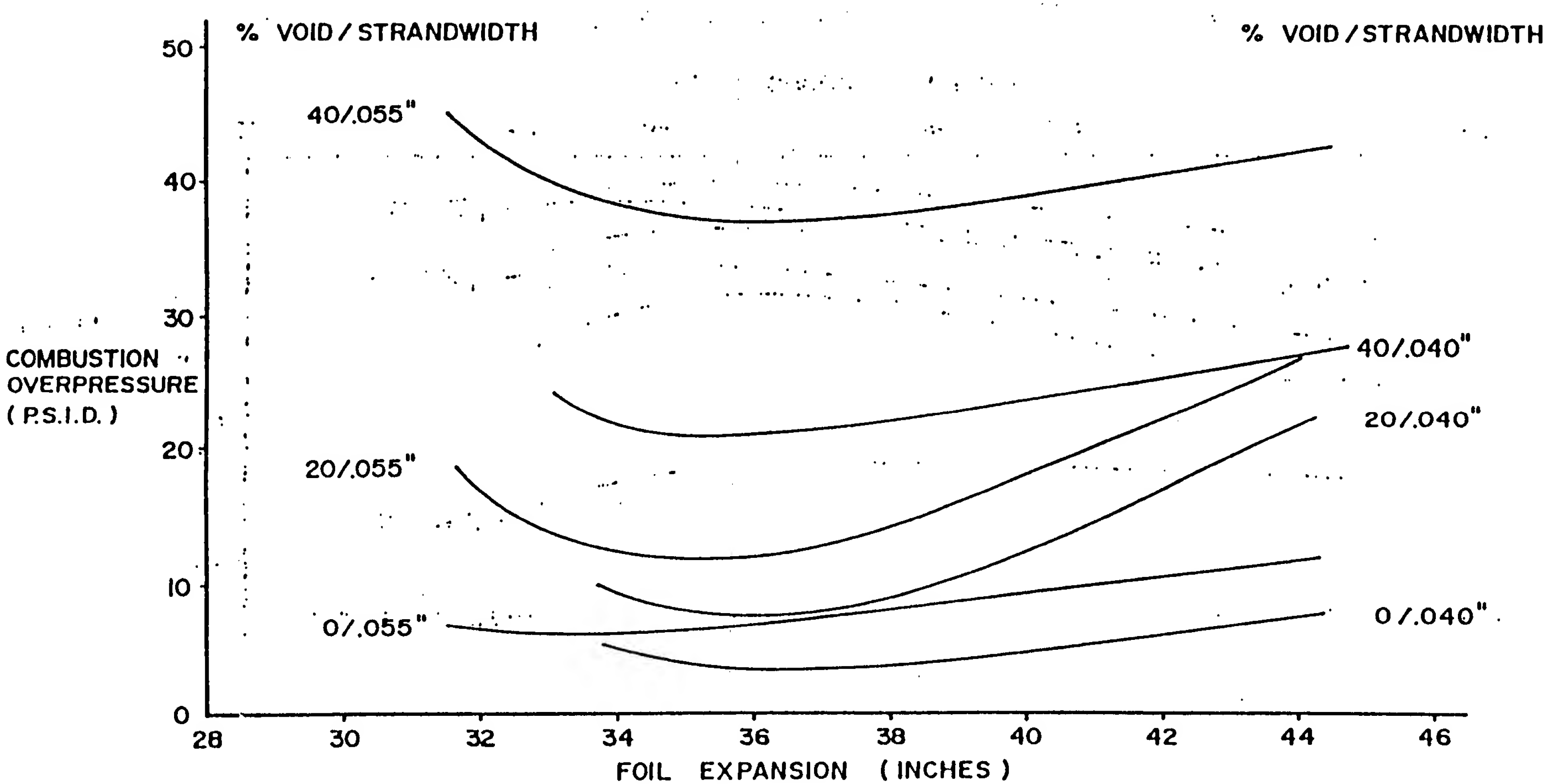

Figure 10. Effect of Strand Width on Combustion Overpressure - 3 psig

The smaller cells consistently result in reduced overpressure and it is believed this is due to the quenching effects argued in the foregoing paragraphs. Further study of this phenomena, using combustion efficiency measurements, will yield a more definite conclusion.

During the testing of the reduced strand width foil, measurements of flame propagation speeds were made and yielded greater insight into the materials' ability to control the combustion reaction. The results are recorded in Table 3. Figure 11 depicts the flame propagation speeds in the fully packed configuration ($V_c = 0$) and, here, the primary reason for the shape of the suppression vs expansion characteristics is apparent. It has been deduced that the cell geometry relates the turbulence of the reaction and the porosity of the material in an inverse manner, i.e. as the cells are reduced in size the turbulence increases and the porosity reduces. At some point these parameters combine to yield a minimum flame propagation speed, which, in turn, extends the duration of the reaction so that the heat is released over a longer time allowing greater heat absorption and reduced overpressure.

Summarizing, the material suppresses combustion overpressure in four ways:

a) by the amount of heat absorption, which is related to specific weight,
b) by the rate of heat absorption, which is related to surface area,
c) by the amount of heat release of the combustion reaction, which is related to the quenching controlled by cell geometry,
d) by the rate of heat release, which is related to flame propagation speed controlled by cell geometry.

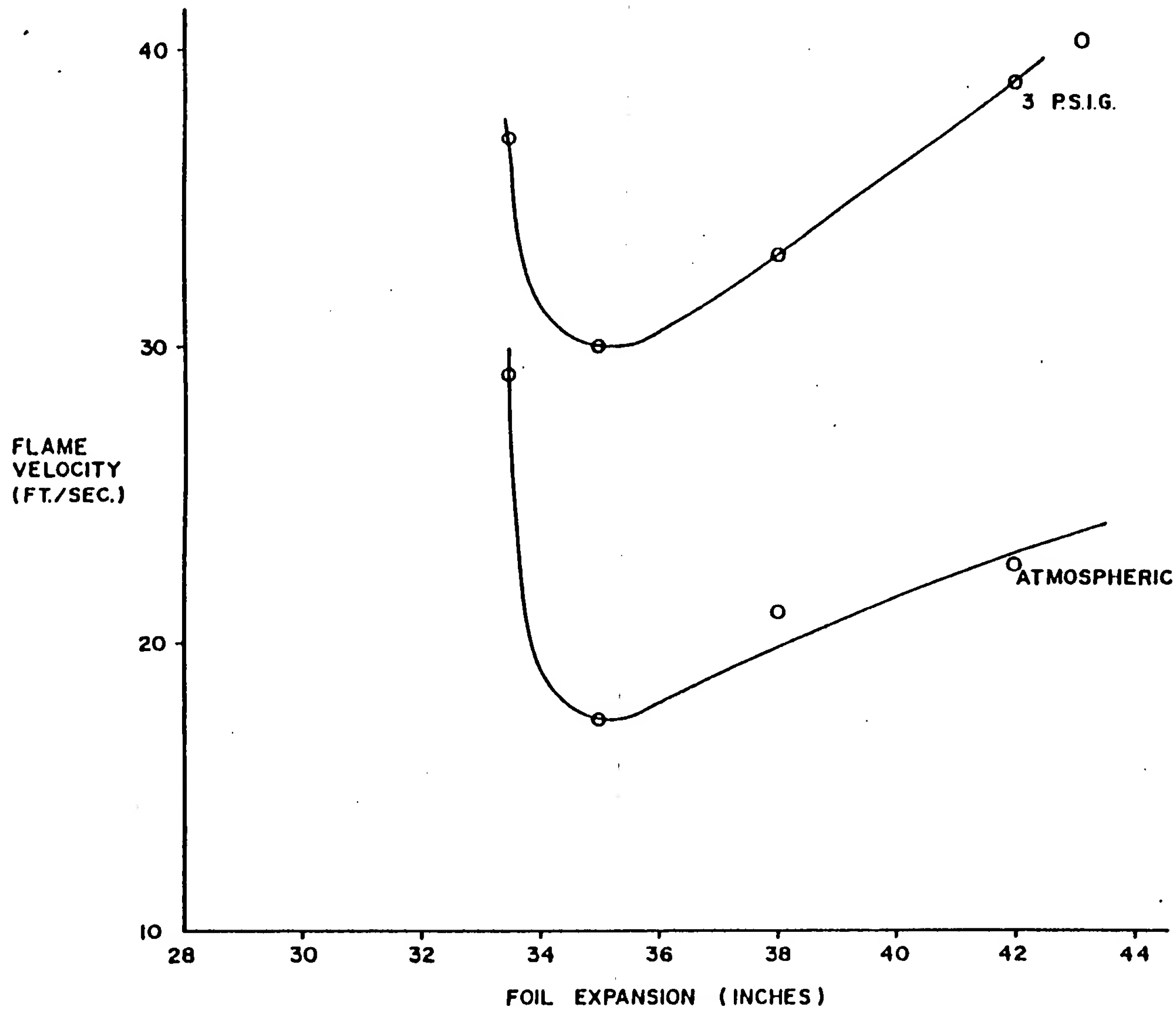

Figure 11. Effect of Foil Expansion on Flame Propagation Speed

1.3 Conclusions

The purpose of evaluating the Explosafe material in the 'worst case' conditions of the flame tube was to define an optimum material with regard to weight, preferably having comparable suppression performance to the polyurethane foams in use by the USAF. Tolerable void level with respect to acceptable overpressure and durability of the material during handling and installation were additional factors to be considered in the selection process. The optimum material was then to be used in the remaining tests of the joint USAF/U.S. Army and VIPL program where the material would be evaluated for aircraft use.

After evaluating each of the material thicknesses over the range of specific weights offered, the 2 mil material at approximately 2 lb/ft^3 was determined to be the optimum. MIL-B-83054B, the specification for polyurethane foam, requires that at a void level of 20% and an initial pressure of 17.7 psia, the combustion overpressure in the flame tube test shall not exceed 15 psid. With the selected Explosafe material, a maximum void level of only 10% is permissible in order to meet the overpressure limit. The 3 mil material offered better performance and could tolerate higher void levels but the weight penalty was greater. The 1.5 mil material offered substantial weight savings but overpressures exceeded 15 psid with a 10% void.

The 2 lb/ft^3 material is a little lighter than that which in this gauge yielded the best performance - the 36 inch expansion 2.1 lb/ft^3 type. In the event that better performance was more important than weight, this density could be specified. Conversely, if weight consideration was more important than performance and/or the application was capable of withstanding higher overpressure, then a lighter density or higher void level could be specified.

The durability of the 2 mil/3 mil materials was considered satisfactory. The 1.5 mil material was easily deformed.

1.4 Recommendations

The alternative strand width material, .040 rather than .055 inch, has demonstrated significant improvement in performance without incurring weight penalty. The tests were only conducted on the 3 mil material and were carried out by VIPL. It is recommended that more extensive testing be conducted by VIPL using the 2 mil material. If the testing confirms the improved performance, then AFWAL should undertake to validate the results with their own test program. The change offers three possible benefits - significant weight savings, higher permissible void level, or extension of the system to pressure limited applications.

It is also recommended that in the interest of further weight reduction, means of increasing the durability of the 1.5 mil material be explored.

2.0 BALLISTICS

2.1 Procedure - Rigid Tank

A ballistic optimization program was conducted by the Applied Technology Laboratory, U.S. Army and Mobility R & D Laboratories (SAVDL-EU-MOS), Fort Eustis,Virginia. The work is fully reported in Reference 3 and the test procedure and results will be summarized in this report for completeness.

The concept of the ballistic test is to determine the effectiveness of an explosion suppression system in a typical environment by direct measurement of the combustion pressure attenuation. To this end, a rigid, rectangular steel tank capable of withstanding both the high explosive blast of typical projectiles and the subsequent fuel/air combustion overpressure is used as a test chamber. The volume of the basic chamber can be increased by the removal of sidepanels and the addition of extension tanks on up to three sides. The basic tank and the tank with all extensions are illustrated in Figures 12, and 13, respectively. During the course of the testing, it was decided to conduct further tests on the 2 mil material in an intermediate tank volume made up of the basic tank plus the aft extension only, as illustrated in Figure 14.